

## Executive Summary

At tens of thousands of sites around the United States, contaminated groundwater and soil are being treated with natural processes. Natural processes have been used alone, without engineered steps to enhance them, at more than 15,000 sites where fuels from underground storage tanks have leaked into groundwater. At an increasing number of other types of sites as well, legal documents are codifying full or partial reliance on natural processes to control contamination. The increasing dependence on natural processes in site cleanup is a result in part of wider recognition that under the right conditions, certain contaminants can degrade or transform in the subsurface without human intervention. In part, it is also a result of the high costs of engineered cleanup systems.

Use of unenhanced natural processes as part of a site remediation strategy is called “natural attenuation.” Some processes that occur during natural attenuation can transform contaminants to less harmful forms or immobilize them to reduce risks. Such transformation and immobilization processes result from biological, chemical, and physical reactions that take place in the subsurface. These reactions may include biodegradation by subsurface microbes, reactions with naturally occurring chemicals, and sorption on the geologic media that store groundwater in the subsurface. Other natural processes dilute the contaminants or transfer them from water to air. Regulatory definitions of natural attenuation generally include all types of processes that can reduce the concentration of a contaminant in water.

Despite its increasing use, the inclusion of natural attenuation in formal plans for waste site remediation can be controversial, especially at large sites where an active public is involved. Members of communities near contaminated sites often believe that natural attenuation is a “do-nothing” approach. They believe that relying on natural attenuation relieves those responsible for the contamination from the financial burden of site remediation without adequately protecting public health and the environment. This controversy is fueled by the difficulty, from a scientific perspective, of determining whether apparent losses of contaminants are due to their natural transformation to less hazardous forms, dilution, or transfer to another environmental medium. Inclusion of dilution and volatilization in the regulatory definition of natural attenuation has added to the controversy because of some people’s philosophical objection to using dilution as a remedy for pollution.

The purpose of this report is to examine public concerns about natural attenuation, the scientific bases for natural attenuation, and the criteria for evaluating the potential success or failure of natural attenuation. The report was prepared by the National Research Council’s (NRC’s) Committee on Intrinsic Remediation. The NRC appointed this committee in 1997 in response to concerns from some scientists that the use of natural attenuation may be outpacing scientific understanding and from others that unwarranted doubts about natural attenuation are preventing its wider use. The committee included members with expertise in all of the scientific disciplines needed to understand natural subsurface processes, the effects of these processes on contaminants, and sociopolitical factors that influence the selection of remedies for contaminated sites. Committee members were drawn from academia, government laboratories, consulting firms, industry, and environmental groups to represent a balance of experience and political viewpoints. This report reflects the consensus of the full committee. The findings are based on the expertise of committee members, careful review of numerous documents and protocols concerning natural attenuation, interviews with other

experts and community leaders involved at contaminated sites, and four public information-gathering meetings.

The principal findings of this report are that natural attenuation is an established remedy for only a few types of contaminants, that rigorous protocols are needed to ensure that natural attenuation potential is analyzed properly, and that natural attenuation should be accepted as a formal remedy for contamination only when the processes are documented to be working and are sustainable. Further, where communities are affected by contamination, community members must be provided with documentation of these processes and an opportunity to participate in decision making.

## **COMMUNITY CONCERNS ABOUT NATURAL ATTENUATION**

At sites where communities are aware of groundwater contamination, community representatives often express significant reservations about using natural attenuation as a formal remedy for the contamination. Due to several widely reported cases of illnesses caused by environmental contamination, these community members may believe that groundwater contamination poses a high level of risk to their health. For example, a survey of residents near Michigan Superfund sites found that the residents, on average, ranked contaminated sites as having a risk of 4.7 on a scale of 1–5 (where 5 represents the highest risk). Community members affected by contaminated sites usually want the contamination cleaned up as quickly as possible. They are likely to object to any remedy that involves leaving a significant amount of contamination in place without on-site treatment to reduce the risks. Although engineered cleanup systems can leave contamination in place for a long time due to technical difficulties, community members often perceive natural attenuation as unlike engineered systems because the method does not use visible contaminant treatment.

Community leaders interviewed as part of this study expressed special concern that natural attenuation allows responsible parties to save on cleanup costs while exposing the community to undue risks. Community leaders believed that in many cases, natural attenuation leads to reductions in contaminant concentrations primarily because the contaminants are diluted or transferred to another environmental medium, where they may continue to pose risks. They indicated a greater willingness to accept natural attenuation if responsible parties and regulators can provide evidence that natural processes operating at their site can transform contaminants to harmless by-products. However, they would be unwilling to accept natural attenuation when contaminant concentration decreases are due to dilution, dispersion, and other processes that move the contamination without necessarily transforming it.

Although community interest will vary on a site-by-site basis, public involvement in decision making is especially important at sites where natural attenuation is proposed as a remedy because of the unique concerns that community members may have about natural attenuation, compared to engineered remedies. Currently, opportunities for public involvement in decision making are limited at most sites. The public usually is not invited to comment until after those responsible for the contamination (known as the responsible parties) and environmental regulators have completed their site investigations and identified candidate remedies. As a consequence, the public may mistrust the choices outlined by the responsible parties and, ultimately, the remedy selected by the regulatory agency. At this stage, public outcry can lead to delays in the remediation process. Although involving the public early may slow the initial stages of remedy selection, studies have shown that early public involvement can reduce these delays in the long run.

Requirements for public participation need not be any different at sites using natural attenuation remedies than at other sites, but existing public participation programs are inadequate to address the special concerns about natural attenuation. Public participation programs for contaminated sites must be reexamined in light of the increasing use of natural attenuation. This reexamination will have to recognize that to date, the majority of sites at which natural attenuation has been used are small sites, usually gas stations, where underground storage tanks have leaked. The public typically is not involved in decision making at these sites. As a result, experience with public involvement at larger, more complex sites with an active affected community is limited. Three key principles that have emerged from studies of community involvement are to (1) involve the community early, (2) provide the community with the resources to participate in the decision-making process, and (3) build an effective working relationship with the community.

### **RECOMMENDATIONS: INVOLVING THE PUBLIC**

- At sites where natural attenuation is proposed as a formal remedy for groundwater contamination and where the contamination affects a community, environmental agencies and responsible parties should provide the community with clear evidence indicating which natural attenuation processes are responsible for the loss of contaminants. The evidence provided should emphasize biological degradation, chemical degradation, and/or physical immobilization processes that reduce the hazard of the contaminants. The evidence should be made available to the public in a transparent, easy-to-understand format.

- Federal and state environmental regulations and guidelines for cleaning up contaminated sites affecting communities should be changed to allow community involvement as soon as the presence of contamination is confirmed. Current regulations provide for community involvement only after a list of potential remedies has been proposed. The restoration advisory boards established as formal venues for community involvement in the cleanup of Department of Defense installations could serve as useful models. Programs for community involvement may have to vary depending on the nature of the contaminated site (i.e., whether the site is a gas station with a small fuel leak and no affected neighbors, or a complex Superfund site in a populated area).

- Environmental regulatory agencies and responsible parties should encourage affected community members to become involved as advisers in decision making at and oversight of contaminated sites. Community involvement should be sought as soon as contamination is discovered. Community input would be valuable in addressing issues such as definition of cleanup goals, identification of areas for testing, evaluation of remedial options, determination of a reasonable time frame for remediation, assessment of the potential effectiveness of institutional controls, and planning of how to conduct long-term monitoring of contaminant concentrations. Strategies for encouraging public involvement include providing information regularly, holding meetings at times and locations that are convenient to the community, establishing rules for community participation at all meetings, using culturally sensitive materials, and where appropriate, translating materials for non-English-speaking communities.

- The Environmental Protection Agency, state environmental agencies, and responsible parties should ensure that interested community groups can obtain independent technical advice about natural attenuation and other potential remedies. The opportunity to obtain this advice should be timely, and the advice should be

provided by an objective source. Providing financial resources to obtain technical advice may be appropriate in some circumstances.

- Environmental regulatory agencies and responsible parties should ensure that interested community members can obtain all data concerning the contamination, health effects, and potential remedies at sites where communities are affected by groundwater contamination. Information should be available at a central repository throughout the site assessment and cleanup process. Clear documentation should be provided to explain how, when, and where data were collected. Data should be provided free of charge or at minimal cost.

## **SCIENTIFIC BASIS FOR NATURAL ATTENUATION**

The Environmental Protection Agency (EPA) and its state-level counterparts are receiving an increasing number of proposals to use natural attenuation in place of or in conjunction with engineered systems for cleanup of a wide variety of contaminants, including chlorinated organic chemicals, explosives, metals, and radionuclides, in addition to gasoline and other fuels. Although natural attenuation has been well documented as a method for treating the fuel components benzene, toluene, ethylbenzene, and xylene (BTEX), currently it is not well established as a treatment for most other common classes of groundwater contaminants. Under limited circumstances, it can be applied at sites contaminated with other types of compounds, such as chlorinated solvents and metals, but its successful use will depend on attenuation rates, site conditions, and the level of scientific understanding of processes that affect the contaminant. In some cases, natural attenuation will be effective only at sites with special environmental conditions conducive to attenuation of the contaminant in question. In other cases, the use of natural attenuation is problematic because scientific understanding is too limited to predict with sufficient confidence whether this strategy will protect public health and the environment.

Natural attenuation processes are contaminant specific. Each contaminant tends to be unique in the way different environmental processes affect its fate. Hence, making generalizations that apply to all contaminants is inappropriate. Especially significant is the difference between organic and inorganic contaminants: Although natural attenuation reactions can completely convert some organic contaminants to carbon dioxide and water, they can alter the mobility of metals but cannot destroy them.

A range of complicating factors can affect natural attenuation potential. One is that the success of natural attenuation depends on the hydrogeology and geochemistry of the site in question. The types of settings that provide the most favorable conditions for natural attenuation depend on the type of contaminant. A second complication is that environmental conditions can vary with time, changing the effectiveness of natural attenuation even at a site where this method initially is capable of controlling contamination. Another is that mixtures of contaminants, which occur commonly, behave differently than individual contaminants because of the many interconnecting processes involved. Finally, some natural processes transform contaminants to forms that are less harmful to humans and the environment, but others form products that are more hazardous or more mobile in the environment than the parent contaminant. An example of the latter is incomplete degradation of trichloroethylene (TCE). When TCE is not fully degraded, vinyl chloride (an intermediate compound that is more carcinogenic than TCE) may form and not completely degrade under certain conditions.

Table ES-1 shows the likelihood that natural attenuation will succeed as the key part of a site cleanup strategy for different contaminant classes. This table should serve only as a general guide; every site will have to be assessed individually because of the wide

variation in conditions at individual sites. Judgments in the table are based on the current level of understanding of the dominant attenuation processes and the probability that sites will have the specific conditions necessary for effective natural attenuation. The second column identifies the processes that are likely to be most important in the destruction or immobilization of the contaminants. Several other attenuation processes may occur for a given contaminant, but the ones listed are the major detoxification mechanisms. The third column indicates whether the level of scientific understanding of the dominant processes is high, medium, or low. The fourth column indicates the likelihood of success of natural attenuation.

## **CONCLUSIONS: NATURAL ATTENUATION POTENTIAL**

- Natural attenuation is well established as a remediation approach for only a few types of contaminants, primarily BTEX. For most other contaminant classes, it is not as likely to succeed or not well established. In some cases, the likelihood of success is low because contaminant degradation or immobilization depends on special environmental conditions that are uncommon. The likelihood of success is also rated as low if the possible production of toxic intermediate compounds could raise regulatory or public concerns about the long-term acceptability of the process. Finally, potential for success is low if scientific understanding is too limited to evaluate the effectiveness of natural attenuation.

- Natural attenuation should never be considered a default or presumptive remedy. Although natural attenuation can protect human health and the environment under the right conditions, its probable effectiveness must be documented at every site (even those contaminated with BTEX) where its use is proposed as a formal remedy for contamination under an environmental regulatory program. The level of documentation required varies considerably depending on the complexity of the site. For example, because BTEX attenuation processes are well understood, sites such as gas stations with BTEX contaminants will not require the same level of analysis as sites with contaminants that degrade less readily or are less well understood.

- To achieve remediation objectives, natural attenuation may have to continue for many years or decades. The time required for natural attenuation will vary considerably with site conditions. At some sites, concentrations will decrease relatively rapidly, whereas at others, the decrease will occur very slowly.

- Natural attenuation of some compounds can form hazardous by-products that in some cases can persist in the environment. For sites with contaminants that have the potential to form such by-products, evidence should be provided to demonstrate that the contaminants are completely transformed to nontoxic compounds.

- Natural attenuation processes cannot destroy metals but in some cases can immobilize them. The passage of time can either enhance or reverse immobilization reactions, depending on the type of reaction, the contaminant, and environmental conditions.

- The presence of contaminant mixtures can enhance or inhibit natural attenuation of any one component of the mixture. In some cases, the presence of co-contaminants is necessary for natural attenuation reactions to occur, but in other cases co-contaminants can interfere with these processes. For example, the presence of fuels can enhance the biodegradation of chlorinated solvents, whereas the presence of contaminants that decrease pH can interfere with the immobilization of metals.

- In some cases, removing contaminant sources can speed natural attenuation, but in other cases it can interfere with natural attenuation. Removing sources can reduce the mass of contamination that has to be treated by natural processes. However, in

some cases, it can cut off natural attenuation entirely, if the source is serving as critical fuel for attenuation processes.

## **APPROACHES FOR EVALUATING NATURAL ATTENUATION**

Documenting that the contaminant concentration has become very low or undetectable in groundwater samples is an important piece of evidence that natural attenuation is working. However, such documentation is not sufficient to show that natural attenuation is protecting human health and the environment, for three primary reasons. First, contaminants can bypass sampling locations due to the complex nature of groundwater systems. Second, in some cases the contaminant concentration may have decreased in one well, but the contaminant may have moved to a new location where it still poses risks, or it may have changed to another, equally hazardous chemical form. Third, in some cases the reactions that initially cause contaminants to attenuate may not be sustainable for the life of the contamination. This last case occurs when natural subsurface chemicals that support attenuation are used up before the treatment of contamination is complete. For these reasons, environmental regulators and others should not rely on simple rules of thumb (such as maximum contaminant concentration data or trends in these data over a relatively short time) in evaluating the potential success of natural attenuation.

The decision to rely on natural attenuation and the confirmation that it continues to work depend on linking measurements from the site to a site model and “footprints” of the underlying mechanisms. Footprints generally are concentration changes in reactants (in addition to the contaminants) or products of the biogeochemical processes that transform or immobilize the contaminants. Footprints can be measured to document that these transformation or immobilization processes are active at the site. Footprints occur because the processes leading to degradation or transformation also consume or produce other materials, such as oxygen, inorganic carbon, and chloride. Many of these other materials can be detected in groundwater samples. An observation of the loss of a contaminant, coupled to observation of one or (preferably) several footprints, helps to establish which processes are responsible for attenuation of contaminant concentrations.

The three basic steps to document natural attenuation are as follows:

1. Develop a conceptual model of the site: The model should show where and how fast the groundwater flows, where the contaminants are located and at what concentrations, and which types of natural processes could theoretically affect the contaminants.
2. Analyze site measurements: Samples of groundwater should be analyzed chemically to look for footprints of the natural attenuation processes and to determine whether natural attenuation processes are sufficient to control the contamination.
3. Monitor the site: The site should be monitored until regulatory requirements are achieved to ensure that documented attenuation processes continue to occur.

Although the basic steps are the same for all sites, the level of effort needed to carry out these steps varies substantially with the complexity of the site and the likelihood that the contaminant is controlled by a natural attenuation process. A much greater effort is necessary when the site is complex and the likelihood of success (as indicated in Table ES-1) is lower than when the site is simple and contaminated with easily degraded compounds such as petroleum fuels. When site characteristics or the controlling mechanisms are uncertain, a large amount of data will be required to document natural

attenuation. In these complex situations, sophisticated computer modeling will be necessary, and data on footprints and site characteristics will have to be adequate to develop the model. Nonetheless, the broad principles of analysis are the same for all types of sites. Table ES-2 shows the level of analysis required for different site - conditions.

### **RECOMMENDATIONS: EVALUATING NATURAL ATTENUATION**

- At every site where natural attenuation is being considered as a formal remedy for groundwater contamination, responsible parties should use footprints of natural attenuation processes to document which mechanisms are responsible for observed decreases in contaminant concentration. Observing the disappearance of a contaminant is important evidence that natural attenuation is working, but it is not sufficient by itself. Footprints are well established for some biodegradation reactions, such as for fuels and chlorinated solvents. Footprints for other contaminants should be based on known biogeochemical reactions. Observing several different footprints and correlating them with decreases in contaminant concentration add to the weight of evidence for natural attenuation. The level of detail needed to analyze footprints varies considerably depending on the complexity of the site, as shown in Table ES-2.

- Responsible parties should prepare a conceptual model of sites being considered for natural attenuation to show where the groundwater and contamination are moving. The conceptual model should show the groundwater flow, contaminant source, plume, and reactions and chemical species relating to natural attenuation at the site. The model should be tested and revised as new data are gathered, especially at complex sites.

- Responsible parties should analyze field data on natural attenuation at a level commensurate with the complexity of the site and the contaminant type. A higher level of effort is needed to document natural attenuation for sites at which the uncertainty is greater due to site or contaminant characteristics, as shown in Table ES-2.

- A long-term monitoring plan should be specified for every site at which natural attenuation is approved as a formal remedy for contamination. Monitoring should take place as long as natural attenuation is necessary to protect public health and the environment. The required monitoring frequency will have to vary substantially depending on site conditions and the degree of confidence in the sustainability of natural attenuation. Simple sites contaminated with low concentrations of BTEX will not require the same degree of monitoring as complex sites with higher concentrations of recalcitrant contaminants.

### **PROTOCOLS FOR NATURAL ATTENUATION**

Within the past few years, many organizations have issued documents providing guidance on evaluating natural attenuation. The Committee on Intrinsic Remediation reviewed 14 of the available natural attenuation documents in detail. These 14 documents were developed by a range of organizations—from federal and state agencies, to private companies, to industry associations. At the time this report was written, they represented most of the available guidelines for evaluating natural attenuation. Although the existing documents serve as valuable guides for conducting studies of natural attenuation potential and summarizing the state of the art, shortcomings will have to be addressed as the proposals to use natural attenuation increase.

With the exception of a Department of Energy (DOE) document, the available technical protocols address only organic contaminants and only two classes of these:

fuel hydrocarbons and chlorinated solvents. A large body of empirical evidence and scientific and engineering studies in recent years has been developed to support understanding of natural attenuation of these contaminants—especially fuel hydrocarbons under certain conditions. However, the natural attenuation of polycyclic aromatic hydrocarbons, polychlorinated biphenyls, explosives, and other classes of persistent organic contaminants is not addressed in any protocol. Furthermore, although the DOE document proposes a method for assessing natural attenuation processes for inorganic contaminants, such processes are extremely complex, and the DOE document does not adequately reflect this complexity. The DOE document has to be peer reviewed and substantially revised before it is used as a decision-making tool.

The committee compared the available guidelines on natural attenuation against a list of characteristics of a comprehensive protocol. A comprehensive protocol should cover three broad subject areas:

1. *Community concerns:* The protocol should describe a plan for involving the affected community in decision making, maintaining institutional controls to restrict use of the site until cleanup goals are achieved, and implementing contingency measures if natural attenuation fails to perform as expected.

2. *Scientific and technical issues:* The protocol should describe how to document which natural attenuation processes are responsible for observed decreases in contaminant concentrations, how to assess the site for contaminant source and hydrogeologic characteristics that affect natural attenuation, and how to assess the sustainability of natural attenuation over the long term. It should be independently peer reviewed.

3. *Implementation issues:* The protocol should be easy to follow and should describe which qualifications site personnel must have in order to implement it.

Table ES-3 summarizes the committee's review. As the table indicates, none of the reviewed documents fulfills all of the criteria defined by the committee. To some extent, this reflects the various, and sometimes limited, purposes for which these documents were prepared. Some are detailed technical guides; others are intended to help ensure consistency in site evaluation within a particular organization (such as a private corporation or a branch of the military); and others are intended to guide policy. Nonetheless, key gaps in the existing body of protocols have to be addressed.

The existing protocols provide little or no discussion of when and how to involve the public in site decisions and when and how to implement institutional controls. In the few instances where these matters are mentioned, the discussion is typically brief, almost in passing. Although most environmental regulatory agencies have separate policies that specify procedures for community involvement and institutional controls, these procedures may be inadequate in cases where natural attenuation is selected as the remedy.

Discussion of when and how to implement contingency plans in case natural attenuation does not work also is inadequate in many of the protocols. Further, the protocols provide insufficient guidance on when engineered methods to remove or contain sources of contamination benefit natural attenuation and when they interfere with it. Guidance on how to conduct long-term monitoring to ensure that natural attenuation remains protective of public health and the environment is inadequate, as well. In addition, the protocols do not describe the level of training needed for implementation.

An additional limitation of some of the protocols relates to “scoring systems” used for initial screening to determine whether a site has potential for treatment by natural attenuation. Such scoring systems yield a numeric value for the site in question. If this



value is above a certain level, the site is judged an eligible candidate for natural attenuation. Frequently, such scores are used inappropriately as the key factor in deciding whether natural attenuation can be a successful remedy at the site. Moreover, these scores often lead to erroneous conclusions about whether natural attenuation will or will not succeed, due to the complexity of the processes involved and the tendency of scoring systems to oversimplify them.

An additional problem is lack of sufficient guidance on which protocols are appropriate for use in various regulatory programs. EPA does not officially endorse any protocols other than those developed by the agency, and the specific information that individual EPA regulators require to document natural attenuation can vary substantially. Similarly, decision processes used by regulators at the state level vary widely. Some state regulators use their own rules of thumb for deciding whether natural attenuation is appropriate, whereas others use established protocols. Although some flexibility is necessary to reflect the varying requirements of different states and regulatory programs, additional guidelines on the use of protocols in regulatory programs would improve the decision-making process. The EPA, as the national environmental regulatory agency, has to take charge of developing such guidelines.

A final shortcoming is that, for the most part, the existing technical protocols have not been independently peer reviewed. Some of the protocols were internally reviewed by the authoring organization or were reviewed informally, but formal, well-documented peer reviews were not conducted. Such reviews are essential to ensure that the protocols are scientifically sound and unbiased.

In summary, the existing body of natural attenuation protocols is limited in several important areas. Where and how existing protocols can be used to meet regulatory requirements for documenting site cleanup—and whether such protocols are required at all—is also unclear. Guidance on the use of natural attenuation for remediation has to be developed to cover topics that are not addressed in existing protocols and to provide for the use of protocols in regulatory programs.

### **RECOMMENDATIONS: IMPROVING PROTOCOLS**

- The EPA should lead an effort to develop national consensus guidelines for protocols on natural attenuation. As soon as possible, the EPA should undertake an effort to work with other federal agencies, state environmental regulators, professional organizations, industry groups, and community environmental organizations to assess natural attenuation protocols and how they can be used in existing regulatory programs (including Superfund, the Resource Conservation and Recovery Act corrective action program, and the leaking underground storage tank program). Ideally, these guidelines should address in detail the attributes listed across the top of Table ES-3. The guidelines should be updated regularly to include new knowledge and should allow flexibility for regional geologic differences and variations in policies by state or region. The guidelines should give special attention to community involvement, source removal, long-term monitoring, contingency plans, sustainability of natural attenuation, and training for protocol users.

- The national consensus guidelines and all future natural attenuation protocols should be peer reviewed. The peer review should be conducted by independent experts who are not affiliated with the authoring organization.

- The national consensus guidelines and future protocols should eliminate the use of “scoring systems” for making decisions on natural attenuation. The evaluation methods outlined in Chapter 4 of this report, using conceptual models and footprints of natural attenuation, should replace scoring systems. Scoring systems are generally too

simple to represent the complex processes involved and often are used erroneously in judging the suitability of a site for natural attenuation. For this reason, scoring systems, including the DOE's monitored natural attenuation toolbox and scorecard, should not be used.

- Developers of natural attenuation protocols should write easy-to-understand documents to explain their protocols to nontechnical audiences. Such documents should be made available to interested members of communities near contaminated sites.
- The EPA, other federal and state agencies, and organizations responsible for contaminated sites should provide additional training on natural attenuation concepts for interested regulators, site owners, remediation consultants, and community and environmental groups. The training should be provided by nonpartisan organizations. The cost of attendance should be subsidized for regulators and community group members.

In summary, natural attenuation processes that degrade or transform contaminants can work well in controlling risks from groundwater contamination when the right combination of contaminants and environmental conditions exists. Natural attenuation is most likely to be effective for contaminants that are readily degraded or immobilized under a wide range of environmental conditions. As Table ES-1 indicates, natural attenuation potential is high for BTEX but low or moderate for most other commonly encountered environmental contaminants. For these other contaminants, natural attenuation may work in some cases under very specific site conditions. For all contaminants, natural attenuation will work best when the geologic system is simple enough for the natural attenuation processes to be effectively monitored.

Regardless of how simple or complex the contaminant and its environment are, documenting natural attenuation requires evidence that natural processes at the site are immobilizing or destroying the contamination to an extent that is sufficient to protect public health and the environment. Footprints of the attenuation reactions should serve as the basis for this evidence, and rigorous protocols are needed to ensure that the evidence is sufficient. Further, the public needs to be involved early in the decision making at sites where communities are adversely affected by contamination.

TABLE ES-1 Likelihood of Success of Natural Attenuation

Chemical Class	Dominant Attenuation Processes	Current Level of Understanding <sup>a</sup>	Likelihood of Success Given Current Level of Understanding <sup>b</sup>
<b>Organic</b>			
<b>Hydrocarbons</b>			
BTEX	Biotransformation	High	High
Gasoline, fuel oil	Biotransformation	Moderate	Moderate
Nonvolatile aliphatic compounds	Biotransformation, immobilization	Moderate	Low
Polycyclic aromatic hydrocarbons	Biotransformation, immobilization	Moderate	Low
Creosote	Biotransformation, immobilization	Moderate	Low
<b>Oxygenated hydrocarbons</b>			
Low-molecular-weight alcohols, ketones, esters	Biotransformation	High	High
MTBE	Biotransformation	Moderate	Low
<b>Halogenated aliphatics</b>			
Tetrachloroethene, trichloroethene, carbon tetrachloride	Biotransformation	Moderate	Low
Trichloroethane	Biotransformation, abiotic transformation	Moderate	Low
Methylene chloride	Biotransformation	High	High
Vinyl chloride	Biotransformation	Moderate	Low
Dichloroethene	Biotransformation	Moderate	Low
<b>Halogenated aromatics</b>			
Highly chlorinated PCBs, tetrachlorodibenzofuran, pentachlorophenol, multichlorinated benzenes	Biotransformation, immobilization	Moderate	Low
Less chlorinated PCBs, dioxins	Biotransformation	Moderate	Low
Monochlorobenzene	Biotransformation	Moderate	Moderate
<b>Nitroaromatics</b>			
TNT, RDX	Biotransformation, abiotic transformation, immobilization	Moderate	Low
<b>Inorganic</b>			
<b>Metals</b>			
Ni	Immobilization	Moderate	Moderate
Cu, Zn	Immobilization	Moderate	Moderate
Cd	Immobilization	Moderate	Low
Pb	Immobilization	Moderate	Moderate
Cr	Biotransformation, immobilization	Moderate	Low to moderate
Hg	Biotransformation, immobilization	Moderate	Low
<b>Nonmetals</b>			
As	Biotransformation, immobilization	Moderate	Low
Se	Biotransformation, immobilization	Moderate	Low
<b>Oxyanions</b>			
Nitrate	Biotransformation	High	Low
Perchlorate	Biotransformation	Moderate	Low

Radionuclides			
<sup>60</sup> Co	Immobilization	Moderate	Moderate
<sup>137</sup> Cs	Immobilization	Moderate	Moderate
<sup>3</sup> H	Decay	High	Moderate
<sup>90</sup> Sr	Immobilization	High	Moderate
<sup>99</sup> Tc	Biotransformation, immobilization	Low	Low
<sup>238,239,240</sup> Pu	Immobilization	Moderate	Low
<sup>235,238</sup> U	Biotransformation, immobilization	Moderate	Low

NOTES: Knowledge changes rapidly in the environmental sciences. Some contaminants not rated as having high natural attenuation potential could achieve this status in the future, but this table represents the best understanding of natural attenuation potential at this time.

BTEX = benzene, toluene, ethylbenzene, and xylene; MTBE = methyl *tert*-butyl ether; PCBs = polychlorinated biphenyls; TNT = trinitrotoluene; RDX = royal Dutch explosive.

<sup>a</sup> Levels of understanding: "High" means that there is good scientific understanding of the process involved, and field evidence confirms attenuation processes can protect human health and the environment; "moderate" means that studies confirm the dominant attenuation process occurs but the process is not well understood scientifically; "low" means that scientific understanding is inadequate to judge if and when the dominant process will occur and whether it will be protective.

<sup>b</sup> "Likelihood of success" relates to the probability that, at any given site, natural attenuation of a given contaminant is likely to be protective of human health and the environment. "High" means scientific knowledge and field evidence are sufficient to expect that natural attenuation will protect human health and the environment at more than 75% of contaminated sites. "Moderate" means natural attenuation can be expected to be protective at about half of the sites. "Low" means natural attenuation is expected to be protective at less than 25% of contaminated sites. A "low" rating can also result from a poor level of scientific understanding.

TABLE ES-2 Summary of Typical Effort Required for Site Characterization and Data Interpretation

Site Hydrogeology	Likelihood of Success of Natural Attenuation of the Contaminant of Concern <sup>a</sup>		
	High (e.g., BTEX, alcohols)	Moderate (e.g., monochloro-benzene, Pb)	Low (e.g., MTBE, TCE, <sup>99</sup> Tc)
Simple flow, uniform geochemistry, and low concentrations	1	2	2
Simple flow, small-scale physical or chemical heterogeneity, and medium-high concentrations	2	2	3
Strongly transient flow, large-scale physical or chemical heterogeneity, or high concentrations	2	3	3

NOTES: Level of effort refers to number and frequency of samples taken, parameters analyzed in site samples, and type of data analysis: 1 = low effort; 2 = moderate effort; and 3 = high effort. BTEX = benzene, toluene, ethylbenzene, and xylene; MTBE = methyl *tert*-butyl ether; TCE = trichloroethene.

<sup>a</sup>Likelihood of success refers to judgments in Table ES-1.

TABLE ES-3 Natural Attenuation Policy Statements, Regulations, and Technical Protocols Reviewed

Type of Document	Community Concerns		
	Community Involvement	Institutional Controls, Long-Term Monitoring	Contingency Plans
Policy			
EPA (1999)	X	X	XX
Regulations <sup>a</sup>			
Minnesota (chlorinated solvents, 1997)	—	—	X
New Jersey (1995)	XX	XX	—
Technical			
Chevron (chlorinated solvents, 1997)	—	—	—
RTDF (chlorinated solvents, 1997)	X	—	X
Air Force (chlorinated solvents, 1997)	—	—	X
EPA Region 4 (chlorinated solvents, 1997)	—	X	X
EPA ORD (chlorinated solvents, 1998)	—	—	—
Navy (fuels, 1998)	—	—	X
Air Force (fuels, 1995)	—	X	X
Chevron (fuels, 1995)	—	—	—
ASTM (fuels, 1997)	—	X	XX
API (fuels, 1997)	—	—	—
DOE (inorganic and organic contaminants, 1998)	—	—	—

NOTE: XX = discussed; X = mentioned; — = not discussed or not applicable. ASTM = American Society for Testing and Materials; API = American Petroleum Institute; chlorinated solvents = chlorinated solvents are primary focus of the document; DOE = Department of Energy; EPA = Environmental Protection Agency; ORD = Office of Research and Development; RTDF = Remediation Technologies Development Forum.

<sup>a</sup> The parts of the state regulations that dealt only with natural attenuation were reviewed.

Scientific and Technical Issues										Implementation Issues
Cause and Effect			Site Condition Assessment	Sustainability						
Scope	Science-Based Underpinnings	Evidence	Geological and Hydrological Setting	Source Characterization	Intrinsic Capacity	Complicating Factors	Robustness	Peer Review	Qualifications, Training	Usability
X	—	X	X	X	—	X	—	—	—	—
X	X	X	XX	X	X	—	—	—	—	XX
—	—	—	—	X	—	—	—	—	—	—
—	XX	XX	—	—	—	—	—	—	—	XX
XX	XX	XX	XX	—	X	X	—	—	—	XX
XX	XX	XX	XX	XX	X	—	XX	—	—	XX
XX	XX	XX	XX	XX	X	X	XX	X	—	XX
XX	XX	XX	XX	—	X	XX	X	—	—	XX
XX	XX	XX	XX	XX	XX	X	XX	—	—	XX
—	XX	XX	—	—	—	—	—	—	—	XX
X	XX	XX	XX	X	X	X	XX	XX	—	XX
—	XX	XX	—	—	—	—	—	X	—	XX
X	X	X	—	—	—	—	—	—	—	XX